Still, the rule works for all of these and also for the one unstable protein, which is from the bacterial virus lambda. They found no exceptions to the rule. The investigators are also doing the β-galactosidase–ubiquitin experiment with another protein, dihydrofolate reductase, that is much smaller and different in shape from β-galactosidase.

Even if the N-end rule is correct, there are still some unanswered questions. For example, How does the rule operate? What recognizes the amino-terminal amino acid of proteins, and how does it do it? What determines how much of the amino terminus is clipped after a protein is made? The clipping of the amino terminus exposes amino acids other than methionine to whatever it is that causes the N-end rule to operate. But Varshavsky is unperturbed. He makes an analogy with the genetic code. "The genetic code is very simple," he says, "but the underlying machinery to decode it is extremely complex."

Finally, whatever happened to ubiquitin, which was where the story started? Does it or does it not have anything to do with protein degradation? Varshavsky now thinks that ubiquitin was a red herring. It does not mark proteins for degradation, he says, and is not even added to the amino termini of proteins since, if it were, it would immediately be chopped off. It must be added only at lysine side chains. Its role may be to help destabilize proteins that are already marked for destruction. The N-end rule also helps explain why bacteria, which have no ubiquitin, manage to degrade proteins perfectly well.

It remains to be seen, of course, how general the N-end rule really is. But, more on this subject, undoubtedly, is yet to come. ■ GINA KOLATA

In Search of Dark Matter

Through the telescope, some 90% of the mass in the universe seems to be invisible; in the laboratory, however, a new generation of detectors may bring the dark matter to light

FOR more than a decade now, astronomers and cosmologists have been forced to explain the things they do see by appealing to something they do *not* see—a necessity that gives their field an undeniable air of mysticism. Yet the evidence is compelling. The motions of galaxies, the distribution of galaxies, the very existence of galaxies—even the overall expansion of the universe, all seem to be dominated by a cosmic ectoplasm known as the dark matter. Whatever this stuff is, it comprises as much as 90% of the mass of the universe. It is also utterly invisible. Indeed, it only makes itself felt by its gravitational effects; the ordinary "baryonic" matter that comprises the visible stars and galaxies is only a kind of flotsam, drifting along wherever the dark matter carries it.

From an empirical point of view this situation is unsatisfactory, to say the least. Fortunately, however, it may also be changing. A number of techniques have recently been proposed for detecting the dark matter in the laboratory. These experiments will stretch detector technology to the limit, and a little beyond. But several teams of researchers have begun development work nonetheless. The first clear detection of dark matter—an event as significant as the discovery of the 2.7 K cosmic background radiation in 1965—could conceivably be announced within the next few years.

All the proposed detection techniques are based on the assumption that the dark matter consists of a haze of elementary particles left over from the Big Bang. Presumably, each particle interacts very weakly with ordinary matter, thus rendering the haze invisible. And presumably, each particle also possesses a tiny mass, thus allowing the haze to produce a large gravitational effect. A wide variety of such particles have, in fact, been predicted in the physicists' current theories of grand unification and supersymmetry; they fall broadly into two major classes—light and heavy—and require two corresponding classes of detectors.

Among the light particles, for example, perhaps the likeliest candidate is the so-called axion, which arises in certain versions of quantum chromodynamics. (In technical terms, the axion is needed to explain the absence of CP violations in the strong interactions.) Taken at face value, the axion is elusive in the extreme. Its predicted mass lies somewhere in the range of 10^{-5} to 10^{-2} electron volts, while its coupling to ordinary matter is thought to be a trillion times weaker than the already feeble coupling of neutrinos.

However, as Pierre Sikivie of the University of Florida and his co-workers first pointed out in 1983, the structure of axion theory is such that the particles would have an effective coupling to photons; in fact, in the proper circumstances an axion might be induced to turn into a photon, which could then be detected by conventional means.

Sikivie thus proposes a microwave cavity located in a strong, uniform magnetic field. According to axion equations, he points out, the magnetic field would serve to trigger the conversion, producing a photon with an energy equal to the axion's mass plus its kinetic energy. If one assumes that the axions do comprise the dark matter, then a short cosmological calculation yields an estimated photon frequency of about 2.4 gigahertz, which lies in the microwave region of the spectrum. Thus the microwave cavity: if it is tuned to resonate at precisely the axion frequency, Sikivie says, it will greatly enhance the probability of conversion. With the use of a state-of-the-art cryogenic amplifier, in fact, the axion-generated photon might actually be detectable.

Sikivie and his colleagues at the University of Florida have begun development work on an axion detector, as have several other groups. In fact, one such group, including Adrian Melissinos of the University of Rochester, together with colleagues from Brookhaven National Laboratory and Fermilab, began taking data on 1 August with a small detector located at Brookhaven.

The real challenge in axion detection is not detection per se, Melissinos explains. It is the signal's needle-in-a-haystack aspect. On the one hand the signal itself is thought to be less than 1000 hertz wide. (It would be smeared out slightly because axions orbiting through the galaxy would have a spread of velocities.) On the other hand its location at 2.4 gigahertz is only an estimate, which is why the Brookhaven detector is searching all the way from 1 gigahertz to 6 gigahertz—a region that gives the axion signal 5 million places to hide. "That's an enormous amount of data," says Melissinos. "If we knew exactly where it was, we could get the sensitivity way up just by sitting on that frequency and integrating longer." As it is, however, any practical experiment has to scan its allotted range within a reasonable amount of time; in the case of the Brookhaven experiment, that means scanning from 1 to 6 gigahertz within about a year. Unfortunately, says

Melissinos, given their current apparatus, which features a magnetic field of 6 tesla and a microwave cavity measuring 20 centimeters by 50 centimeters, their sensitivity will be about a factor of 10 too low to detect axions at the coupling strength favored by cosmologists. The group has plans to close the gap later on by enlarging the cavity somewhat and by increasing the magnetic field to 15 tesla. "But it still remains a very tenuous experiment," he says.

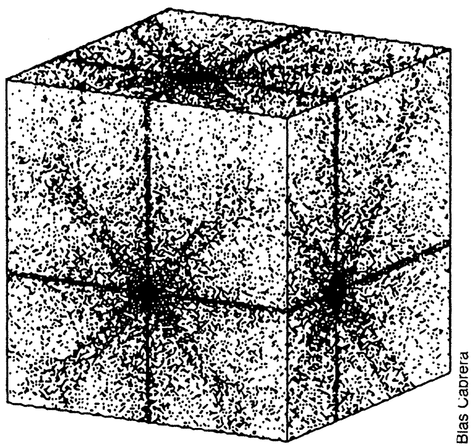
Of course, one could always go to even more ambitious detectors. According to some recent calculations, for example, a cavity having a volume of one cubic meter, placed in a 10-tesla magnetic field, could scan the octave around 2.4 gigahertz in only 24 hours. On the other hand, the microwave cavity resonator approach may not be the last word, either. Sikivie, for example, has suggested another approach in which the photon conversion would be triggered by an interaction with a pair of spin-aligned electrons, as in a block of magnetized iron. If the idea proves feasible, it could lead to detectors substantially more sensitive than those based on the microwave approach.

Meanwhile, a second class of experiments focuses on the detection of heavy dark matter candidates: weakly interacting, massive particles—WIMP's—with masses in the range of 1 GeV to 1 TeV, and with interaction strengths not too different from the conventional weakly interacting particles. A wide variety of candidates have been suggested, including the massive neutrinos predicted in some grand unified theories, and the photinos, gravitinos, Higgsinos, or scalar neutrinos predicted by models incorporating supersymmetry.

The fundamental idea in this class of experiments is to set aside a chunk of mass—the detector—and then wait for a WIMP to strike an atomic nucleus somewhere inside; the experimental signal is the recoil of the nucleus. First proposed in the early 1980's by Leo Stodolsky of the Max Planck Institute in Garching, West Germany, and Andrjei K. Drukier of the Harvard-Smithsonian Center for Astrophysics, the recoil technique was originally seen as a way of detecting low-energy neutrinos; its utility for detecting WIMP's was only pointed out in 1984 by M. K. Goodman and Edward Witten of the Institute for Advanced Studies in Princeton. Its great advantage is that atomic nuclei happen to fall in the mass range of 1 GeV (hydrogen) to a few hundred gigaelectron volts (uranium), which is roughly the same range of masses occupied by the conjectured WIMP's. Since energy is transferred most efficiently in a collision when the two objects are of equal mass, a judicious choice of target nuclei can thus produce a detector of maximal sensitivity.

Furthermore, the quantum wavelength of a galactic dark matter particle would be considerably larger than the size of a nucleus, which means that a passing WIMP has a chance to scatter coherently from all the protons and neutrons of the target nucleus simultaneously. In fact, if the WIMP-nucleus forces are independent of spin—that is, if interaction is via the so-called vector coupling—then the reaction rate would be enhanced by a factor of about 1000 over the incoherent case. This translates into an estimated rate of 100 to 10,000 interaction events per kilogram of target per day, which means that detectors can, in principle, be relatively small and inexpensive.

Unfortunately, the enhancement disappears if the forces are governed by the so-called axial vector coupling, which would only allow the WIMP's to interact with unpaired nuclear spins. The estimated rates



Ballistic phonons in silicon. *A dark matter particle colliding with a nucleus deep in the interior of a crystal would produce a spreading wave of quantized sound waves, or phonons. These phonons in turn would produce a characteristic energy pattern on the crystal surfaces, as this simulation shows.*

in this case are on the order of one event per kilogram per day. On the other hand, this drawback can be overcome by going to a larger-mass target made up of elements chosen for their high-spin nuclei, so it need not be fatal. The real challenge of the recoil approach lies in the magnitude of the effect. A WIMP orbiting in the galaxy will transfer only a few thousand electron volts (KeV) of energy at most; measuring the effects of a single recoil inside a macroscopic block of material is thus a daunting task. Indeed, the fundamental problem is not so much detection per se, but eliminating the background effects that swamp the signal.

The biggest culprit turns out to be contamination from naturally occurring radioactive elements, which are ubiquitous at the levels appropriate for a WIMP search. And perhaps the best example of what it takes to eliminate that contamination is the ultralow background detector developed over the past 5 years by Ronald L. Brodzinski of Battelle Pacific Northwest Laboratories, Frank Avignone of the University of South Carolina, and their colleagues. As a WIMP detector the apparatus is at best a prototype—it is primarily intended to search for the double beta-decay of neutrons, another phenomenon predicted by the grand unified theories—but it has been able to place some useful constraints on the WIMP mass and interaction strength nonetheless.

At heart the device is simply a standard germanium spectrometer, a 0.72-kilogram semiconductor crystal that provides an environment where incoming particles can create electron-hole pairs; when the pairs later recombine, they emit a characteristic pulse that allows for a determination of the original particle's energy. However, this particular spectrometer has received special treatment. After testing their apparatus above ground, Brodzinski and Avignone moved it to the Homestake gold mine in Lead, South Dakota, where it resides next to the Brookhaven solar neutrino experiment some 1600 meters underground. At that depth the detector was reasonably well protected from cosmic rays. But this simply meant that the researchers had to contend with radioactive emissions from the surrounding rocks. The obvious way to eliminate such interference is to encircle the apparatus with a shield of some sort, which Brodzinski and Avignone did. However, after some trial and error they found that they had to supplement their original shield with an inner shield made of 448-year-old lead ballast weights recovered from a sunken Spanish galleon. Modern lead turns out to have a measurable concentration of radioactive species produced by cosmic rays while it is exposed on the surface of the earth. But after nearly five centuries protected by deep water, the old lead was virtually inert.

Meanwhile, the researchers had to rebuild their electronics: the solder turned out to contain a radioactive isotope of polonium. And so it went. Their reward for such exertions is a detector with a background rate of about 100 counts per kilogram of detector per day, or about three orders of magnitude lower than the rate in conventional low-background detectors. Indeed, after about 10 weeks of taking data at the highest sensitivity, Brodzinski, Avignone, and their colleagues have been able to rule out the existence of galactic WIMP's over a wide range of masses and interaction strengths. For example, if the WIMP's are assumed to interact with nuclei via spin-independent weak interactions (or more technically, through the exchange of a Z vector boson), then their mass has to lie outside the range of 20 GeV to 5 TeV.

The team plans to continue in their efforts to reduce background. However, it must be said that instruments of this type have some fundamental limitations as WIMP detectors. For example, a germanium nucleus recoiling from a WIMP interaction is not very effective at making electron-hole pairs. At energies below about 1 keV, in fact, the WIMP signal would be lost in the intrinsic noise of the amplifier. Furthermore, most germanium nuclei have spin zero, which means that only the germanium-73 component—8% of the total—will respond to axially coupled WIMP's such as the photino. In short, to do substantially better one has to go to cryogenic detectors. Several such devices have in fact been proposed.

Perhaps the simplest is a bolometric detector proposed in 1985 by Blas Cabrera of Stanford University, Lawrence M. Krauss of Harvard University, and Frank Wilczek of the University of California, Santa Barbara. Their design is based on the fact that, at temperatures near absolute zero, the specific heat of most materials becomes vanishingly small. (It is proportional to the cube of the absolute temperature.) Thus, a very small energy transfer can result in a measurable temperature change in macroscopic masses. For example, in the case of a 1-kilogram detector made of silicon, which has favorable thermodynamic properties, and which is readily available in a very pure form from the electronics industry, Cabrera, Krauss, and Wilczek find that an energy transfer of 100 keV will cause the temperature to rise from 1 millikelvin to 4 millikelvin. Measuring such a temperature rise is challenging, but feasible, they argue. Indeed, the effect has already been demonstrated with much smaller silicon crystals.

A silicon bolometric detector of this type is currently under active development by Bernard Sadoulet of the University of California, Berkeley. On the other hand, the bolometric approach does have its drawbacks, which have led Cabrera and his colleagues at Stanford to study a variant.

The main problem with the bolometric approach, Cabrera explains, is that it only provides information about the energy of the interaction event, not its location in the crystal. But locational information is important for rejecting background events: a cosmic ray, for example, would tend to leave a trail of many interactions, whereas a real WIMP or a real neutrino would produce precisely one interaction.

Thus, instead of measuring the overall temperature rise that the interaction event produces in the detector crystal, Cabrera proposes to listen for the sound it makes. More precisely, his idea is to mount an array of sensors on each surface of the crystal, and thereby map out the characteristic pattern of ballistic phonons—quantized sound waves—as they strike the surfaces. From the pattern he can then reconstruct the energy and location of the event.

The ballistic phonon approach is ambitious even by WIMP-detector standards. But, with the use of superconducting tunnel junctions as the sensors, Cabrera believes that he can achieve a spatial resolution of about 0.25 millimeters in a 1-kilogram silicon detector, and an energy threshold of about 1 KeV, which would put it right in the range for dark matter. He and his colleagues have already begun development work on the device.

The real challenge in axion detection is the signal's needle-in-a-haystack aspect.

Yet another approach to heavy WIMP detection is the superheated superconducting colloid detector (SSCD), a concept that has evolved during the past several years through the work of Drukier and his collaborators.

As the name suggests, an SSCD would consist of a myriad tiny grains of superconducting material, each in the form of a sphere about 20 micrometers across, suspended in a dielectric material. In operation the device would be placed in a strong magnetic field and cooled just below the superconductor's transition temperature; in effect, each grain would be balanced on the brink of normality. The idea is that a WIMP-nucleus collision would upset the balance, depositing enough energy to tip the affected grain into a normal state. At that point the magnetic field, which had been forced to bend around the superconducting grain because of the Meissner effect, would suddenly be able to penetrate the grain's interior. This change in the field would be the experimental signature: in mathematical terms it would be equivalent to the flip of a tiny dipole, and could be detected by a superconducting quantum interference device, or SQUID.

The sensitivity of a SSCD would depend on precisely how it is made, as well as the precise distribution of WIMP's in the solar neighborhood. However, using reasonable models of both detector and WIMP's, Drukier and his colleagues estimate that a SSCD could detect particles with masses as low as 2 GeV. In addition to detecting the WIMP's, moreover, an SSCD could go a long way towards identifying them. Since there are more than 20 elements suitable for making the superconducting grains, one can choose from a wide variety of nuclear masses and spins. Tin, for example, seems to be an excellent material for detecting massive neutrinos and scalar neutrinos, while aluminum seems especially well suited for detecting photinos. One can even imagine combination SSCD's made with several different types of grains.

Finally, says Drukier, the SSCD detector could provide information about the mass and velocity distribution of the WIMP's; the experimenter simply has to vary the SSCD's magnetic field and operating temperature, which has the effect of changing the detection threshold. In fact, he and his colleagues argue that the device could measure an annual rise and fall in the WIMP signal due to the earth's motion around the sun; if so, this variation would greatly help in separating the signal from the background.

For all its advantages, the SSCD presents some obvious challenges, not the least of which is the production of several trillion micrometer-sized grains of uniform size and sphericity. Nonetheless, some early experiments look promising. Stodolsky and his collaborators have begun an intensive development effort in Europe, while Drukier, Avignone, and a number of other U.S. researchers have recently joined forces for a similar effort in this country.

It should be clear from the foregoing discussion that the ideas for dark matter detectors are very much in flux; indeed, there is still plenty of room for totally new ideas. On the other hand, momentum is clearly building. "Where we'll end up on this, I don't know," says Drukier. "All these ideas represent good technologies. But what we need are good feasibility studies so that eventually, in a few years, we can join forces in a one or two full-scale efforts." ■

M. MITCHELL WALDROP

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